Constraints on the Interaction between Dark Matter and Baryons from Cooling Flow Clusters

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Other nongravitational heating processes are needed to resolve the disagreement between the absence of cool gas components in the centers of galaxy clusters revealed recently by Chandra and XMM observations and the expectations of conventional radiative cooling models. Here we propose that the interaction between dark matter particles and ordinary baryonic matter may act as an alternative for the reheating of intracluster medium (ICM) in the inner regions of clusters, in which kinetic energy of dark matter is transported to ICM to balance the radiative cooling. Using the Chandra and XMM data of typical clusters, we set a useful constraint on the dark matter-baryon cross-section: $\sigma_{xp}/m_x \sim 1 \times 10^{-25}$ cm^{2}GeV^{-1}, where m_x is the mass of dark matter particles.

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The standard view of the cold dark matter (CDM) assumes that dark matter consists of massive particles with weak interactions with ordinary baryonic matter, as well as with weak self-interactions. This scenario has proved to be very successful in explaining the origin and evolution of cosmic structures on large scales, but may conflict with astrophysical observations on galactic and subgalactic scales. Many attempts have thus been made in recent years to modify the standard CDM model. For example, the CDM particles may be self-interacting [1], or the dark matter particles could be warm [2].

While it is widely believed that the interaction of dark matter with ordinary matter is weak, the alternative picture, in which dark matter interacts strongly with ordinary matter, still remains an interesting issue. Indeed, a decade ago, Starkman *et al.* [3] surveyed all current observations and experiments and found that there exist several allowed regions for the dark matter consisting of strongly interacting massive particles (SIMPs) which have large cross-sections with ordinary matter.

Recently Wandelt *et al.* [4] have re-evaluated the issue and presented a new constraint on SIMPs. Adding in the results from new experiments, they found that their stringent constraint allows a region in which $\sigma_{xp}/m_x \sim 10^{-26} - 10^{-24}$ cm^{2}GeV^{-1}, with $m_x > 10^5$GeV, where σ_{xp} is the dark matter-proton cross-section, m_x and m_p are the masses of dark matter particles and protons, respectively. Interestingly, this cross-section is similar to both the ordinary hadron-hadron cross-section σ_{pp}/m_p, and the dark matter-dark matter cross-section $\sigma_{xx}/m_x = 8 \times 10^{-25} - 1 \times 10^{-23}$ cm^{2}GeV^{-1} in the self-interacting CDM scenario proposed by Spergel and Steinhardt [1]. In fact, it was the striking similarity between σ_{xx}/m_x and σ_{pp}/m_p that had led Wandelt *et al.* to address the possibility that dark matter particles may interact strongly with ordinary baryonic matter as well as with themselves. It was argued that if the dark matter consists of an exotic, neutral and stable hadron which does not radiate photons or other massless mesons, then the hadron will act like dissipationless, collisional dark matter.

On the other hand, recent high resolution observations of the hot X-ray emitting intra-cluster medium (ICM) in cooling flow galaxy clusters with the new generation X-ray satellites Chandra [5] and XMM [6] [7] bring new puzzle to astrophysicists. It has long been realized that the radiative cooling, due to thermal bremsstrahlung, in the central regions of cooling-flow clusters is normally a rapid process, compared with the dynamical time of the system. For typical rich clusters, the central cooling time is less than 10^9 yr, an order of magnitude shorter than the Hubble time (see, e.g. Refs. [8] [9]). Hence, the ICM near the cluster centers should be found to be considerably cooler than that of the outer regions.

With unprecedentedly high spatial resolution and sensitivity, the Chandra/XMM observations have revealed detailed temperature structures down to a few kpc from the centers of nearby clusters. Although a radial temperature gradient is clearly observed in each cluster, the cooled gas component with temperatures lower than ~ 2 keV is prominently absent and the central ICM temperature is only found to be slightly lower than that of the outer regions. This seems to challenge conventional theoretical expectations.

Various possibilities have been suggested to explain this discrepancy [7], which can be essentially classified into three categories. 1. Some additional heating mechanism, although still very uncertain, is needed to provide extra energy to the ICM in cluster centers and hence to temper the cooling process, quickly reheating the cool gas back to the hot phase. 2. The gas has rapidly cooled below ~ 2 keV and we therefore do not see it. 3. The cool gas may exist, but its emission is absorbed by cold material at the center of the flow. Further X-ray observations are thus required to distinguish these possibilities.

Yet, an alternative scenario is that the above inconsistency with the conventional cluster cooling picture may be alleviated if dark matter interacts strongly with ordinary baryonic matter. This is because dark matter

may serve as a heating source to transport its kinetic energy to ICM. Therefore, the problem we will address is twofold: First, it provides a natural resolution to the absence of the cool ICM components below ~ 2 keV in cluster centers. Second, study of the distributions of the ICM density and temperature in clusters may allow us to set useful constraints on the dark matter-baryon cross-section σ_{xp}.

In galaxy clusters, dark matter particles and protons have similar rms velocities as they trace the same underlying gravitational potential. However, the "temperature" of the dark matter particles should be much higher than that of the protons within the framework of the standard CDM model. This simply arises from the fact that CDM particles are much heavier than protons.

Now we consider that the protons and dark matter particles have Maxwellian velocity distributions with velocity dispersions σ_p and σ_x, respectively. For a proton and a dark matter particle having velocities $\mathbf{u}$ and $\mathbf{v}$ in the lab frame and colliding at relative velocity $\mathbf{s} = \mathbf{u} - \mathbf{v}$, the proton's outgoing speed in the center of mass (CM) frame will be s. Averaged over all the directions, the proton's kinetic energy in the lab frame will be $m_p(s^2+v^2)/2$ which gives the averged energy gain of the proton to be $m_p(s^2+v^2-u^2)/2$. Therefore the energy transfer rate from dark matter to protons is

$$\frac{dE}{dt\,dV} = \frac{m_p n_p n_x \sigma_{xp}}{4(2\pi)^3 \sigma_x^3 \sigma_p^3} \int du\, 4\pi u^2 e^{-u^2/2\sigma_p^2} \times \int dv\, 4\pi v^2 e^{-v^2/2\sigma_x^2} \int_{-1}^{1} d\cos\theta\, (s^2+v^2-u^2) s, \quad (1)$$

where $\cos\theta \equiv \mathbf{u}\cdot\mathbf{v}/uv$, and n_p and n_x are the number densities of protons and dark matter particles, respectively. It follows that the temperature change of the protons due to the heating of dark matter particles is

$$\frac{d\ln T}{dt} = \frac{n_x \sigma_{xp}}{3\pi \sigma_x^3 \sigma_p^5} \int du\, u e^{-u^2/2\sigma_p^2} \int dv\, v e^{-v^2/2\sigma_x^2} f(u,v), \quad (2)$$

where

$$f(u,v) = \frac{(u+v)^5 - \mid u-v \mid^5}{5} + (v^2-u^2)\frac{(u+v)^3 - \mid u-v \mid^3}{3}. \quad (3)$$

Experiencing the same graviational field, the protons and dark matter particles in a galaxy cluster should have similar velocity dispersions. The place that one needs to be careful is the cluster center where the radiative cooling is the most rapid. However, as discovered recently by the Chandra and XMM observations, the cooling process in the central regions of galaxy clusters is probably very inefficient and much slower than theoretical expectations (see below for further explanations). Therefore, it appears a reasonable approximation to assume that the protons and dark matter have the same velocity dispersion. Thus, for simplicity, we take $\sigma_p = \sigma_x = \sigma$ in our evaluation. Integrating the right-hand side of Eq.(2), we finally obtain the equation describing the heating process of protons by dark matter:

$$dT_{\rm heating} = \frac{25}{2\sqrt{\pi}} n_x \sigma_{xp} \sigma T dt \quad (4)$$

Recall the definition of the cooling time $t_c \equiv -d\ln T/dt$ [8], which gives $dT_{\rm cooling} = -T\,dt/t_c$. Now the overall cooling process of clusters is described by

$$dT = -T\,dt/t_c', \quad (5)$$

where

$$\frac{1}{t_c'} = \frac{1}{t_c} - \frac{25}{2\sqrt{\pi}} n_x \sigma_{xp} \sigma. \quad (6)$$

From the cluster temperature profiles observed by Chandra and XMM, the central temperatures of ICM is approximately half of the global values, which indicates that the cooling in cluster centers has been greatly tempered, and that t_c', the quantity characterizing the "actual" cooling process, should be comparable to the cluster age of $\sim 10^{10}$ yr. On the other hand, by measuring the electron density and temperature, Chandra and XMM have already obtained detailed information about t_c. For the central regions of radii $r \sim 100$ kpc, t_c is only a few Gyr. And for the innermost regions of a few kpc, t_c reaches its lowest value of about 3×10^8 yr. This yields that $t_c' \gg t_c$, and hence we can set a constraint on the dark matter-baryon cross-section

$$\frac{\sigma_{xp}}{m_x} = \frac{2\sqrt{\pi}}{25} \frac{1}{\rho_x\, \sigma\, t_c}, \quad (7)$$

where $\rho_x = m_x n_x$ is the dark matter mass density.

From strong gravitational lensing observations, Tyson *et al.* [10] obtained a detailed mass map in the central region of the cluster CL0024+1654, which does not contain a central cD galaxy, and found the existence of a $35h^{-1}$ kpc soft core (where $h \equiv H_0/100$, and H_0 is the Hubble constant in units of $\mathrm{km\,s^{-1}\,Mpc^{-1}}$). In particular, Firmani *et al.* [11] presented an analysis of the halo mass for dwarf galaxies, low surface brightness galaxies, and clusters of galaxies, and concluded that the halo central density is nearly independent of the total mass over a broad mass range with an average value of $\sim 0.02 M_\odot/pc^3$. Taking this characteristic value, together with the typical values of X-ray clusters, we have

$$\frac{\sigma_{xp}}{m_x} = 6\times 10^{-26}\,\mathrm{cm^2\,GeV^{-1}} \left(\frac{\rho_x}{0.02 M_\odot\,\mathrm{pc^{-3}}}\right)^{-1} \times \left(\frac{\sigma}{1000\,\mathrm{km\,s^{-1}}}\right)^{-1} \left(\frac{t_c}{10^9\,\mathrm{yr}}\right)^{-1}. \quad (8)$$

Note that ρ_x, σ and t_c are not independent of each other. The right-hand side of Eq.(7) can be further simplified by the employment of the cooling time estimate in terms of thermal bremsstrahlung [8] $t_c = 1 \times 10^9 \mathrm{yr}\,(n_e/0.1\mathrm{cm}^{-3})^{-1}(T/10^8\mathrm{K})^{1/2}$, where n_e is the electron density which can be derived from X-ray observations. Alternatively, we introduce the local baryon fraction $\tilde{f}_b$ such that $\rho_x = \tilde{f}_b^{-1}\,\mu_e m_p n_e$, where $\mu_e = 1.13$. Moreover, we replace the proton velocity dispersion σ by the ICM temperature T through $m_p\sigma^2 \approx kT$, where k is the Boltzmann constant. Finally, the cross-section σ_{xp} is written as

$$\frac{\sigma_{xp}}{m_x} = 9 \times 10^{-26}\,\mathrm{cm}^2\,\mathrm{GeV}^{-1}\left(\frac{\tilde{f}_b}{0.1}\right)\left(\frac{T}{5\times 10^7\,\mathrm{K}}\right)^{-1}. \tag{9}$$

The radial dependence of the quantity $\tilde{f}_b(r)$ resembles approximately that of the volume-averaged baryon fraction f_b. The latter appears to be a slowly increasing function of radius (see, e.g. Ref. [12] and references therein), similar to the radial variation of the ICM temperature T as indicated by Chandra and XMM measurements. As a result, the overall effect of $\tilde{f}_b$ and T makes the right-hand side of Eq.(9) roughly constant, or insensitive to cluster radius.

For typical clusters, it is appropiate to choose $T = 5 \times 10^7$ K and $\tilde{f}_b = 0.1$ in Eq.(9), or $\sigma = 1000$ $\mathrm{km\,s}^{-1}$ and $t_c = 5 \times 10^8$ yr in Eq.(8) for cluster central regions, which gives $\sigma_{xp}/m_x \sim 1{\times}10^{-25}$ $\mathrm{cm}^2\mathrm{GeV}^{-1}$. The σ_{xp}/m_x value we obtained for the dark matter-baryon interaction is in good agreement with Wandelt *et al.*'s findings [4] in their exclusion plot. Moreover, it is similar to the σ_{pp}/m_p value for the ordinary hadron-hadron strong interaction, and also near the lower end of the σ_{xx}/m_x value for the dark matter-dark matter interaction in the self-interacting CDM scenario [1],

Clearly, our σ_{xp}/m_x value is suggestive of a strong interaction between dark matter and ordinary baryonic matter, which challenges the conventional views towards dark matter that the dark matter particles interact weakly with ordinary matter. Detailed theoretical and experimental discussions and explanations on SIMPs have been presented in full length by Starkman *et al.* [3] and Wandelt *et al.* [4]. In this paper, we have no intention to enter into the exploration of the particle physics of SIMPs. Rather, we would like to give an empirical evaluation of SIMPs from recent astronomical observations of cooling flow clusters.

To summarize, in this paper we have proposed that the puzzle with the cooling picture of galaxy clusters, arised from recent Chandra and XMM high resolution observations, could be naturally settled if we assume that dark matter interacts strongly with ordinary matter. This interaction provides a new heating mechanism for the baryons in some gravitationally bound dynamical systems like galaxy clusters. Using the typical properties of density and temperature of ICM revealed by Chandra and XMM, we have set a useful constraint on the dark matter-baryon cross-section $\sigma_{xp}/m_x \sim 1 \times 10^{-25}$ $\mathrm{cm}^2\mathrm{GeV}^{-1}$. This estimate is consistent with earlier findings of Refs. [3] and [4] from a combined analysis of the existing experimental/observational constraints.

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